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The influence of exploration activities of a potential lithium mine to the environment in Western Serbia

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The proposed exploitation of the Jadar Valley lithium/borate deposit in Serbia, by the Rio Tinto Corporation, indicates that it would become large-scale processing of boron- and lithium-containing ore. It would be one of the world's very first lithium mines in populated and agricultural area. The company claims that the envisioned mining will be in accordance with environmental protection requirements. The Jadar Valley deposits have been claimed to cover 90% of Europe's current lithium needs. Yet, local opposition to the mining has arisen due to potential devastating impacts on groundwater, soil, water usage, biodiversity loss, and waste accumulation. Research drilling by the mining company has already produced environmental damage, with mine water containing high levels of boron leaking from exploratory wells and causing crops to dry out. Furthermore, our investigations reveal substantially elevated downstream concentrations of boron, arsenic, and lithium in nearby rivers as compared to upstream regions. Additionally, here we show that soil samples exhibit repeated breaches of remediation limit values with environmental consequences on both surface and underground waters. With the opening of the mine, problems will be multiplied by the tailings pond, mine wastewater, noise, air pollution, and light pollution, endangering the lives of numerous local communities and destroying their freshwater sources, agricultural land, livestock, and assets.

The power supply and transportation sectors are the largest global emitters of greenhouse gases (GHGs)—the major drivers of climate change[1]. The adoption of low-carbon technologies is one of the generally accepted measures to minimize the effects of climate change[2]. These modern technologies are heavily reliant on lithium-ion and other batteries that require cobalt, copper, nickel, graphite, manganese, and other metals and minerals[3]. Lithium-ion batteries, capable of storing high density of energy, require new amounts of lithium from nature, partially because the existing batteries are insignificantly recycled[4,5].

Despite lithium's abundance on Earth, there are not many concentrated deposits, or "reserves", that can be profitably extracted[6]. The so-called Lithium Triangle, which includes regions of Chile, Argentina, and Bolivia, contains the majority world's lithium deposits[7]. The largest lithium deposits in the world[8] are stored in the lithium triangle brines (up to 70%) and significantly less in the form of ore rocks (about 10%), among which are spodumene, lepidolite, hectorite, and jadarite[9]. The easiest and least environmentally damaging method of exploiting lithium is from brines, while exploitation from ore rocks has severe environmental consequences[10,11,12]. Therefore, lithium mining is usually conducted in deserts and uninhabited areas of Australia, Chile, China, Argentina, Canada, Zimbabwe, and the United States[13]. Recently, the exploitation of lithium has been considered in two populated areas in Portugal and Serbia[14,15].

As China now controls most of the lithium-ion battery supply chain, with 80% of the world's raw material refining, 77% of the world's cell capacity, and 60% of the world's component manufacturing, the European

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Commission has encouraged mining projects within Europe[16]. Obradovic et al. were the first to report on a high content of lithium and boron in Jadar Valley in 1999[17], Republic of Serbia, and mineral jadarite was characterized in 2007 by Whitfield et al.[18]. According to recent reports[19], the deposits found in Jadar valley are substantial and have the potential to meet up to 90% of Europe's current lithium requirements. Nevertheless, it should be noted that Jadar's lithium content represents only about 1% of global reserves[13].

Rio Tinto, a multinational mining corporation, has been exploring mineral deposits for over 15 years and has planned to open a lithium mine in Serbia. Rio Tinto completed the geological exploratory stage of the Jadar project in January 2020, following multiple experimental drillings aimed at exploring *jadarite*, a new source of lithium[15]. The company received political support from Serbian authorities in June 2021. Our initial results of the analyses of selected chemical elements from the Jadar mining zone in local soil and river water indicate that the environmental impact during the exploration phase is evident around the potential Jadar mine area and exceeds the zone of the planned mine.

Initial exploratory drillings entailed the claims from the local population regarding the observed significant negative effects of groundwater by-production on soil and water quality. Such concerns have been augmented by existing information on the negative impacts of lithium mining on water usage, biodiversity loss, and waste generation elsewhere[20–22]. A petition opposing the mine's opening garnered over 292,000 signatures[23], leading to protests, road blockades, and political tensions[24]. Moreover, the scientific debate has raised concerns over the ecological, environmental, and technological risks, especially considering the questionable technology solutions of *jadarite* processing. Rio Tinto submitted a patent application for a mineral recovery process in 2018, with EPO granting the patent only on July 05, 2024.

Although governmental policies and the industry's push towards sustainable energy sources to reduce CO_2 emissions have been powerful narratives, they have also served as a barrier to discussion on the negative impacts of lithium battery usage, including recycling thereof. Bibliometric research reveals that the majority of published studies come from lithium-consuming countries and predominantly center on the life cycle of the battery and its costs[25]. Only around 5% of these studies focus on the socio-environmental impacts, with just 2% coming from lithium-producing countries[25–29]. This imbalance in information availability presents a major concern and serves as an urgent call to expand the research by including a holistic examination of lithium mineral extraction and its socio-environmental impact.

This paper aims to examine and assess the ecological, eco-chemical, and socio-environmental hazards associated with the experimental drilling activities and the proposed lithium mine in Jadar, Serbia.

Ecological risk assessment of the Jadar lithium mine in Western Serbia

The planned Jadar lithium mine, along with its accompanying infrastructure, production facilities, and at least two landfills, is located in the western part of Serbia near the border with Bosnia and Herzegovina, in an area known for its prosperous agricultural practices. The project would occupy the territory of surrounding villages, which have a population of about 20,000 people[30]. Based on initially presented lifespan of 64 years, the project would result in job losses for thousands of people who currently rely on the area's agricultural industries[30].

The preliminary estimated spatial coverage of the Jadar project is 2031, with 533 ha of land expected to be destroyed during the initial phase of the project implementation. Of the land to be destroyed, 206.5 ha are forests, and 173 ha is arable land. Ore excavation and groundwater pumping or leakage would result in the subsidence of almost 850 ha of land. The establishment of landfills in the immediate coastal zone of Jadar and Korenita Rivers, the extremely torrential local watercourses, would create a constant threat of contamination to downstream sections, endangering the water supply for about 2.5 million people.

The planned tailings landfills, occupying the area of 20 ha and with increase of waste of 360,000 t/yr, as well as industrial waste landfill with an area of 167 hectares with increase of waste of 1.4 Mt/yr[31], loaded with hazardous substances such as boron, arsenic, etc. that would dispose on a 1.5–2 mm thick foil intended to protect groundwater reserves from toxic substance leakage[30]. Also, the tailings landfills would be settled next to Korenita and Jadar rivers, which are prone to heavy flooding of the surrounding areas.

In this region, a unique outcrop of sandy-gravel deposits exists, which is directly connected to practically the entire terrain of Mačva and Jadar region. The deposit's greatest thickness is along the course of the Drina River, ranging from 50 to 75 m, while in the rest of Mačva, it is between 20 and 40 m. This area represents the most significant groundwater reserve in Western Serbia[32].

The implications of the proposed Jadar project causing land degradation and soil erosion, correspond to the term "desertification" and represent a direct negation of the principles of the "RIO" conventions (UNFCC-climate change, UNCBD-biodiversity, UNCCD-fight against desertification and land degradation). Furthermore, the project undermines the United Nations Sustainable Development Goals and the accepted Agenda 2030, as well as domestic legislation related to nature conservation.

The planned "Jadar" project is expected to cause significant habitat destruction and fragmentation, resulting in severe negative impacts on the living world, including several hundred plant and animal species. Among these species, 145 have protected and strictly protected status. The project would also threaten the isolated eastern enclave of *T. scorodonia*, a sub-Atlantic species located more than 600 km away from the nearest western population. Additionally, the rare fern *Dryopteris* and 20 other rare species would disappear from the site of the planned tailings lands, as reported by Krizmanić et al. in 2021[33].

Furthermore, the "Jadar" project is a threat to the existing tourist destination, as well as to over 50 objects of architectural heritage and archaeological sites of historical, cultural, and spiritual significance. In addition to given impacts, our estimation suggests that possible income from agricultural activities, estimated at 81.96 million euros per year (based on 17,000 EUR/ha), by far exceeds the potential of ore rent of 16 million euros (Ergo strategy group, September 2023).

According to recent research[34], old forests can assimilate approximately 1.6–4 t of CO_2 per year; for 204 ha it can be estimated to be 0.32–0.82 kt per year. For agricultural land, assuming a minimum of 0.5 kg per 1 m^2, a carbon assimilation rate of 5 t per hectare, or 1.6 kt per 320 hectares has been estimated[35]. Some of the carbon is transferred into the ground, and large quantities are stored in forest soils[36]. Björheden[37], based on data from Stendahl et al.[38], suggests that the average storage of soil carbon in Swedish forest land is approximately 75 t per hectare, down to a depth of 100 cm, or recalculated to CO_2 gives 275 t. By analogy, the 204 hectares of forest in Serbia planned to be removed due to the project "Jadar" would store about 56 kt of carbon.

The industrial waste landfill is planned in the Štavica stream basin (area of 167 hectares) where about 26,000 m^3 of wood mass would be removed[30]. This amount of forest wood for CO_2 assimilation will be permanently destroyed, which will accelerate soil erosion, drying of springs, the disappearance of the living world in the basin and riverbed, and increase the risk of destructive torrential floods. There are numerous examples in the world where mine waters and the leaching of dangerous substances from mining waste have polluted rivers so much that they have become dead[39–45] including Borska River in eastern Serbia[46], which is so polluted due to mining activities that it has become a dead river and is one of the most polluted rivers in the world.

Eco-chemical risk of jadarite mining and lithium extraction

The extraction process for lithium from *jadarite* ore, as proposed in World Patent application WO 2019/094674 A1, involves digesting the ore utilizing concentrated sulfuric acid (> 95%) at temperatures between 80 and 95 °C and within a pH range of 2.0–3.8. The resulting digestate can would be concentrated and further treated to produce $B(OH)_3$, Li_2CO_3, and Na_2SO_4 as a byproduct. Based on a feasibility study[47], the annual production of Li_2CO_3 would be 58,000 t/year, and $B(OH)_3$ production would reach 286,000 t/year. However, the waste tailings would contain a high concentration of boron and other harmful elements like arsenic and others, making them hazardous waste. The proposed processing of ore (853,333 t/year) would require 320,000 t/year of concentrated H_2SO_4 (94–98%) and various fuels, materials, and other components. Natural gas would likely be the most viable fuel option, and substantial quantities of cement would also be required, and emulsion explosive would be used in substantial quantities.

The investigation phase of the project has had a harmful impact due to the leakage of toxic mine water containing high levels of boron, arsenic, and lithium. These elements have contributed to soil and water pollution in agricultural areas due to the leakage of toxic mine water during the exploration phases. Would the mine be opened, these toxic waters from the depth around the ore body, under pressure of several bars, would come to surface area that is rich in surface- and shallow high-quality groundwater. It will certainly significantly pollute both as well as the surrounding soil.

Despite the proposed announced new technology, the company has been unable to meet legal limit values for boron in soil and water[48]. However, the limit values for boron in water imposed by local laws have been increased[49,50], therefore boron is no longer considered to be harmful substance in soil as well, according to newest regulations in Serbia[51,52]. Our field measurements, conducted at the site where samples were collected, show that toxic groundwater from the ore rock zone (Table S1) has contaminated agricultural fields under crops. Geological structure of the subsoil in the studied area is mainly of carbonate origin. Soil samples from fields with crops were taken from the surface, up to a depth of 5 cm. Samples of surface and underground drinking water, as well as river sediments, were also collected from the middle of the Jadar and Korenita rivers in PE bottles (Table S2). Soil and sediment samples were extracted using the BCR sequential extraction procedure, which includes a residual fraction for elements strongly associated with mineral crystalline structures. Seventeen samples of underground mine water from two wells, provided to local community by the Rio Sava research team, were also analysed. Using the iCAP-6500 Duo inductively coupled plasma optical emission spectrometer (ICP/OES) with an uncertainty of 1%, we determined element concentrations (refer to Supplementary Materials for detailed methods). The accuracy of the obtained results was checked by analysing sediment reference material (BCR-701) for three-step sequential extraction. Accuracy was determined by comparing the measured concentration with the certified value and then expressed in parts per hundred. The average recovery values for heavy metals in the standard reference material were in the range of 82.7–109.5%. Duplicate samples were used to measure the precision of the method. The relative standard deviations of the means of duplicate measurement were less than 10%. Uncertainty of the measurement for all metals was max. 3% while expanded uncertainty with coverage factor 2 was max. 6%.

The elements As, B, and Li are characteristic for the ore body in the Jadar Valley, their simultaneous appearance is the fingerprint of that ore zone. Their simultaneous presence in high concentrations was found in underground mine waters, the soil near the leaking wells and in the Jadar River downstream of the ore zone in the Jadar field, more than 20 km away of the leaking wells. They were not found upstream from would-be mining area in Jadar Valley and Jadar River where their respective concentrations were found to be around, or below, the detection limit either in the soil or distant from the exploration wells. The boron content in the underground mine water exceeded 1 gL^{-1}, and the boron content in the soil around the leaking wells exceeded the limit value defined by earlier legal norms[48] by a factor of four. However, according to new state regulations[51,52], boron content in the soil is no longer regulated at all. The limit value for arsenic has also been exceeded several times (8–9 times); it even exceeded the remedial value (4–5 times), as shown in the Supplementary Material (Tables S3 and S4).

Analysis of the samples revealed that the boron content in the soil around the leaking wells, cadaster parcels No. 259, No. 101/2 (Fig. 1) ranged from 73.2 to 214 mg kg^{-1}, with the readily soluble fraction[53] comprising 96% to 97% of the total boron content in contaminated soil. The crops thrive healthily in areas away from test wells (Fig. 1), while in areas around leaking test wells contaminated with boron, crops are visibly stunted. The presence of boron was not found in areas where the crops were healthy. Although boron is an essential element for plant nutrition nevertheless, boron toxicity can inhibit plant growth in soils. High boron intake in humans can be harmful to stomach, liver, kidneys, and brain and even lead to death[54]. The Ministry of the Environment in

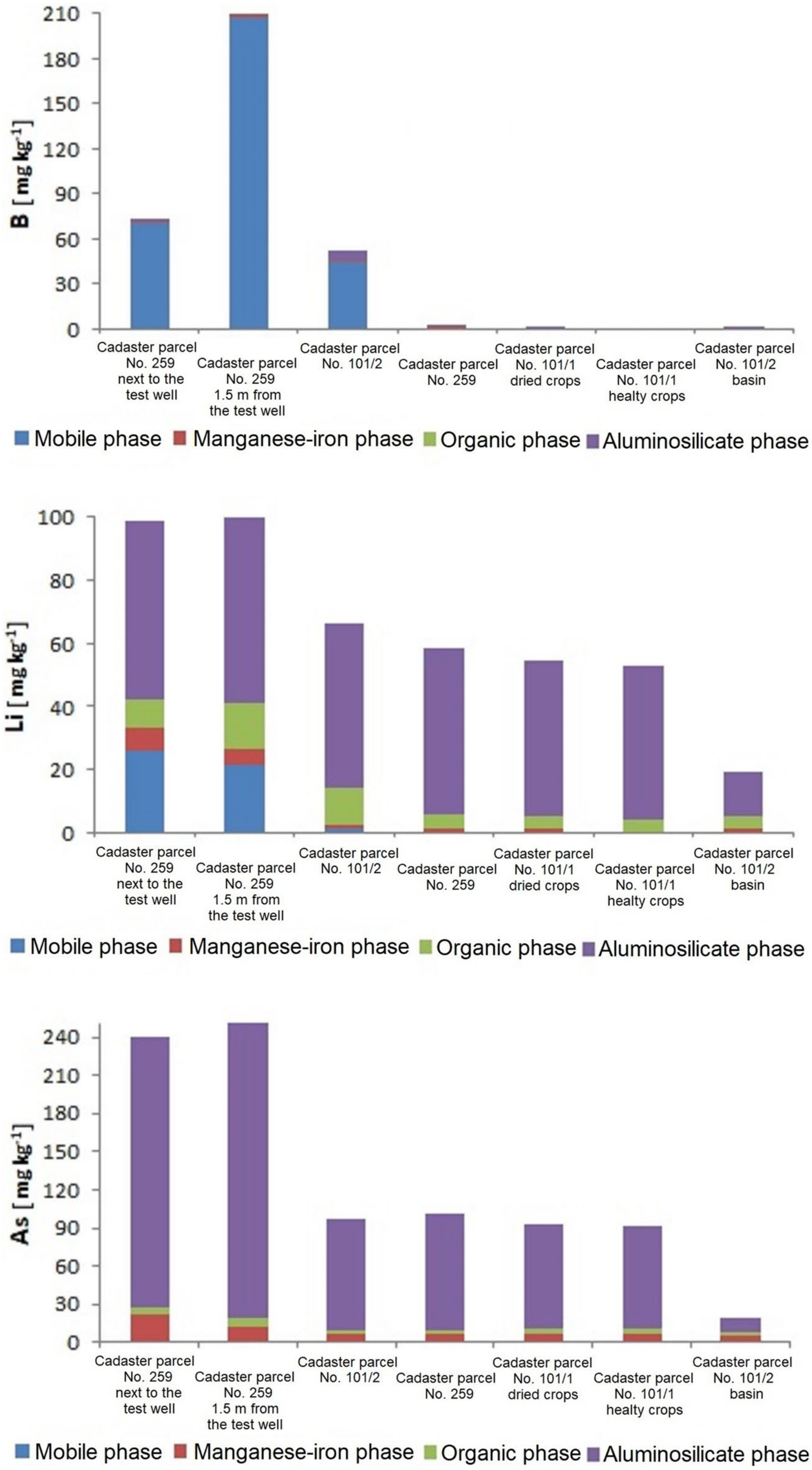

Figure 1. Total content and distributions of As, B, and Li among mobile (blue) and other fixed phases (red, green, and violet) around the leaking test well in agricultural soils.

Ontario, Canada, sets a limit of 36 mg kg^{-1} for boron content in agricultural and other soils[55]. In the soil around the wells that leaked most recently, the content of lithium in the mobile phase is about 30% of total its content found in soil (Fig. 1). The higher mobility of boron compared to lithium determines its higher content in the Jadar River downstream from the mine zone (Fig. 2).

Investigation revealed that the concentrations of arsenic in agricultural soil around the leaking wells exceeded national limit values (29 mg kg^{-1})[51,52] several times, even exceeding the remedial value (55 mg kg^{-1}). According

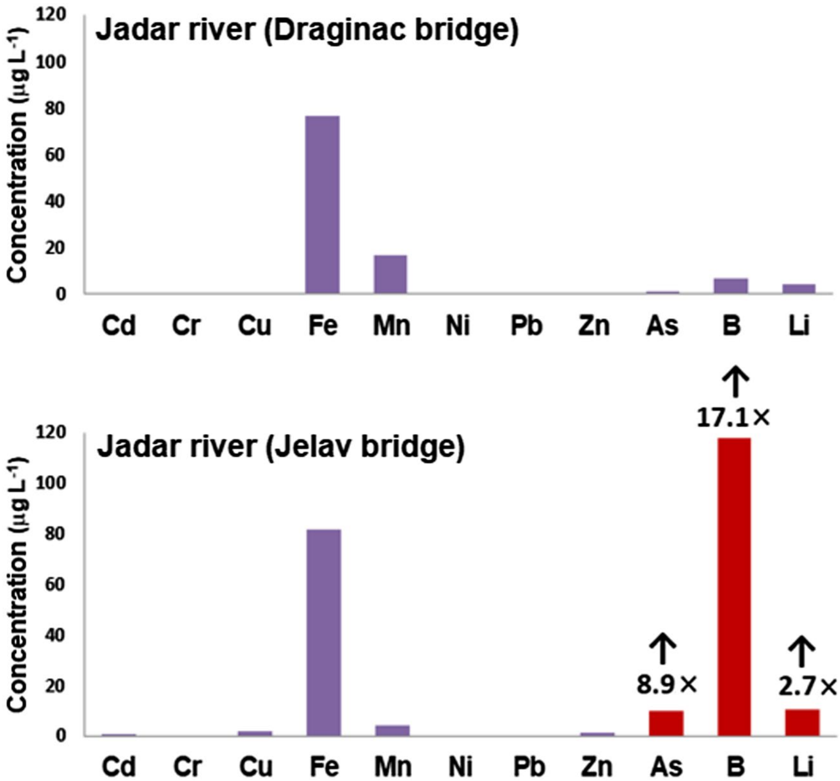

Figure 2. Contents of specific elements in Jadar River (water): (**a**) upstream from the exploratory drillings, (**b**) downstream from exploratory drillings.

to the Ministry of the Environment, Canada, the limit value for arsenic in agricultural soil is 11 mg kg^{-1}, and for residential, parkland, institutional, industrial, commercial, community, or property use, the limit value is 18 mg kg^{-1}[55].

Furthermore, our study revealed that the concentrations of arsenic, boron, and lithium in the water of the Jadar River downstream (Fig. 2) were significantly higher compared to the upstream levels (9, 17, and 3 times higher, respectively, at 25 km downstream compared to 2 km upstream from the potential mine site in Jadar Valley). These results demonstrate the impact of exploration activities on the accumulation of arsenic, boron, and lithium in the water of the Jadar River near its confluence with the international river Drina. These three elements represent the fingerprint of lithium and boron deposit in Jadar.

The problems mentioned in this paper were only related to the investigative activities of the mining company. We predict that with the mine opening, in addition to the presented problems that will multiply, new problems would arise due to tailings the company plans to place next to the two torrential rivers Korenita and Jadar and also in Štavica River valley uphill from the lithium boron mine and ore processing plant. The landfill in Štavica river would block river's free flow and create a pond. We also predict that the mine wastewater with a high risk of endangering the water system on a wider scale will be released, which together with noise, air and light pollution, will endanger the lives of numerous local communities in the immediate vicinity of the mine, agriculture, livestock, beekeeping, etc. We also estimated total yearly CO_2 emission from the Jadar project which would be in the range from 428 to 522 CO_{2eq}/kt per year (Table S5).

Globally, mining of lithium is mostly done only in desert and unpopulated areas of the planet, but Jadar valley is settled area with a very important reservoir of high-quality shallow underground drinking water. In Greenbushes (Australia)[56] there is a mine of lithium ore in an agricultural area and the material is finely crushed and refined and the concentrate is packed for shipping. Very recently, in the relative vicinity of the Greenbushes, the Kemerton lithium project[57] started production of lithium hydroxide from the Greenbushes concentrate, however the Project already faces serious problems nowadays. In addition, the most, if not all of Australia's lithium ore was shipped elsewhere for battery production[58]. Waste from spodumene processing in Australia is not characterized as hazardous waste[59,60], while the processing of jadarite generates dangerous waste due to high content of boron and arsenic in it. Also, in Australia waste does not pile up at (or around) the place of concentrate processing (production, in this case, of lithium hydroxide).

Socio-environmental risks of Rio-Tinto's jadarite mining project in Serbia

A qualitative data analysis conducted in July 2021 in Gornje Nedeljice, a village in Western Serbia, revealed evidence of soil and water pollution, deforestation, as well as forced displacement of the residents, due to the exploration activities by the Rio Tinto Corporation for a potential mine in the area (see Supplementary materials).

Semi-structured interviews were conducted with residents by Jelena Brezjanović, who reported multiple problems since the company began exploring the mine including environmental degradation as well as rising social concerns. During the interview process, detailed field notes were used to reflect on the interviews and observations in the field. The researcher recorded conversations and saved them on a secure, non-shared password-protected device following the University of Belgrade, Institute for Chemistry, Technology and Metallurgy (UB-ICTM), guidelines and regulations regarding participants' rights and data protection. The institutional body approved the research protocol for this study in written form. Additionally, informed consent was obtained from all subjects, and any identifiers were removed from the paper and individuals anonymized. The research protocol has been approved by the Scientific Board of the UB—ICTM which also have the responsibility to protect ethical standards in scientific research in accordance with regulations defined in the Codex of Professional Ethic of University of Belgrade. The Helsinki Declaration which regulates the ethical principles for medical research involving human subjects is not relevant for this research. The current evidence shows that the proposed Jadar Valley mine would adversely impact 22 villages that depend on agriculture by devastating their rich agricultural land, some 14,000 apiaries, and multiple livestock farms[61]. The potential economic loss is intertwined with the rich historical heritage as these residents have been living on this land for generations. The residents strongly oppose the mine's opening and demand the preservation of their land and livelihoods.

During the initial stages of the proposed mining project, some residents allowed sample drilling on their properties without realizing that their land was located on the planned tailings. However, as soon as crop damage (see Fig. 3) and losses of animals in contact with the leached, toxic underground mine water from the drill site became apparent, they raised concerns about the project. Two years later, the company began buying off properties from permanently occupied households, as well as (weekend) cottages, that would be affected by the mining project (Mailer to property owners, October 2020. riotinto.com/Jadar). While some locals sold their homes due to pressure from the company or fear of negative consequences, the others were unaware of their rights. As a result, the remaining residents felt threatened and very much disturbed by the company's strategy of de-roofing the acquired houses, marking them with yellow tape denoting "Private Property, No Trespassing", leaving them to deteriorate as locals interpret, the warning signs. It is important to note that the mining company has aggressively defended its actions and cited the possible economic benefits of the project, while residents have expressed concerns about the environmental and social impacts.

Attempts were made to amend laws related to expropriation and land use to facilitate mining projects, but these changes were met with resistance from activists and were withdrawn by the Government of Serbia[62]. The opening of mines can have significant environmental and health impacts, particularly when decisions are made with a narrow focus on profit. For example, mining activities can result in release of toxic pollutants into the environment, leading to widespread contamination of water and soil, and endangering public health. Furthermore, unchecked competition for resources can have long-term consequences for the environment and future generations. It's important to consider the perspectives of different stakeholders, including mining companies,

Figure 3. Leaking wells: (**a**) Cadaster parcel No. 101/1 cornfield, photo—18th July 2021st; (**b**) Cadaster parcel No. 75/1 field 5th November 2021st, (**c**) Cadaster parcel No. 259 soybean field, photo—18th July 2022nd. Authors are grateful to Mr. Živko Petković (3a), a resident of the village of Gornje Nedeljice, for the photographs taken in the research area of the lithium and boron ore zone in the Jadar Valley.

activists, and government officials when making decisions about mining and resource use. It is true that economic benefits associated with mining projects may arise, it's critical to prioritize environmental protection and public health in order to ensure the sustainable future.

Conclusion

The lithium ore excavation in Western Serbia (Jadar) in a populated and lively agricultural area would be the first and unique such a case in the World. The construction of a mine and processing plant, within the same industrial complex, for the extraction of lithium and boron would destroy the life activities of about 20,000 people of the local community which already make a very good living. The company plans to place a mine and processing plant in the mid of fertile soil surrounded by settlements that resides above the biggest reserve of underground drinking water in western Serbia, and also tailings dump waste between two torrential rivers that are flooding the field every couple of years. The big problem related to the exploitation of lithium in the world is the aggressive chemical extraction process that involves huge amount of concentrated mineral acids, primarily concentrated sulfuric acid. The consumption of enormous amount of water to produce lithium carbonate consequently would generate vast amounts of wastewater which would be of great permanent polluting threat to the surface and underground water. Although it appears that lithium plays a significant role in reducing GHG emissions, a huge amount of energy from fossil fuels are consumed in the process of production of lithium carbonate from ores and CO_2 emissions are significant. Lithium extraction from mines and lithium carbonate production does not contribute to reduction of CO_2 emission.

The lithium deposit in Western Serbia is not worth mining in terms of environmental risks because it is the only one in the world where lithium extraction is planned in a populated and fertile agricultural area, and most importantly it will certainly destroy the one of only three water-bearing areas in Serbia. Also, this deposit with ~ 1% of global lithium reserve does not offer the amount that will solve the climate change problem globally.

Data availability

The data sets used and/or analysed during the current study available from the corresponding author on reasonable request.

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References

1. Climate Watch. *Historical GHG Emissions*. Available online: https://www.climatewatchdata.org/ghg-emissions (2021).
2. National Academies of Sciences, Engineering, and Medicine. *The Future of Electric Power in the United States* (The National Academies Press, 2021). https://doi.org/10.17226/25968.
3. Lèbre, É. *et al.* The social and environmental complexities of extracting energy transition metals. *Nat. Commun.* **11**, 4823. https://doi.org/10.1038/s41467-020-18661-9 (2020).
4. Swain, B. Recovery and recycling of lithium: A review. *Sep. Purif. Technol.* **172**, 388–403 (2017).
5. Yang, Y. Production of lithium metal with ion-selective solid electrolytes. *Green Energy Environ.* **5**(4), 382–384 (2020).
6. Oliveira, L. *et al.* Key issues of lithium-ion batteries–from resource depletion to environmental performance indicators. *J. Clean. Prod.* **108**, 354–362 (2015).
7. Dickson, E. *South America's prospective*. The Lithium Triangle. Resource World (2017).
8. Kesler, S. E. *et al.* Global lithium resources: Relative importance of pegmatite, brine and other deposits. *Ore Geol. Rev.* **48**, 55–69 (2012).
9. Li, H., Eksteen, J. & Kuang, G. Recovery of lithium from mineral resources: State-of-the-art and perspectives—A review. *Hydrometallurgy* **189**, 105129 (2019).
10. Jiang, S. *et al*. Environmental impacts of lithium production showing the importance of primary data of upstream process in life-cycle assessment. *J. Environ. Manage.* **262**, 110253. https://doi.org/10.1016/j.jenvman.2020.110253 (2020).
11. Gu, G., & Gao, T. Sustainable production of lithium salts extraction from ores in China: Cleaner production assessment. *Resour. Policy* **74**, 102261. https://doi.org/10.1016/j.resourpol.2021.102261 (2021).
12. Khakmardan, S. *et al*. Comparative life cycle assessment of lithium mining, extraction, and refining technologies: a global perspective. *Procedia CIRP* **116**, 606–611. http://dx.doi.org/10.1016/j.procir.2023.02.102 (2023).
13. Ambrose, H. & Kendall, A. Understanding the future of lithium: Part 1, resource model. *J. Ind. Ecol.* **24**(1), 80–89 (2020).
14. Barroso Lithium Project. *Savannah Resources*. https://www.savannahresources.com/project/barroso-lithium-project-portugal (2023).
15. Jadar Project. *Rio Tinto*. https://www.riotinto.com/en/operations/projects/jadar (2022).
16. Pisonero, E. C. S. *Jadar Could Be Economic Opportunity if Ecology Standards Met. N1*. Available from: https://rs.n1info.com/english/news/ecs-pisonero-rio-tinto-jadar-project-can-be-good-economic-chance-for-serbia (2022).
17. Obradović, J., Vasić, N., Kašanin-Grubin, M. & Grubin, N. Neogene lacustrine sediments and autillgenic minerals geochemical characteristics. *Ann. Geol. Penins. Balk.* **63**, 135–154 (1999).
18. Whitfield, P. S. *et al.* $LiNaSiB_3O_7(OH)$–novel structure of the new borosilicate mineral jadarite determined from laboratory powder diffraction data. *Acta Crystallogr. B Struct. Sci.* **63**(3), 396–401 (2007).
19. Reuters. *Rio Tinto Keen for Talks to Revive Serbian Lithium Project*. Reuters [Internet]. Available from: https://www.reuters.com/business/rio-tinto-keen-restart-talks-stalled-serbian-lithium-project-2022-05-05 (2022).
20. Baspineiro, C. F., Franco, J. & Flexer, V. Potential water recovery during lithium mining from high salinity brines. *Sci. Total Environ.* **720**, 137523 (2020).
21. Flexer, V., Baspineiro, C. F. & Galli, C. I. Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing. *Sci. Total Environ.* **639**, 1188–1204 (2018).
22. Babidge, S., Kalazich, F., Prieto, M. & Yager, K. 'That's the problem with that lake; it changes sides': Mapping extraction and ecological exhaustion in the Atacama. *J. Polit. Ecol.* **26**(1), 738–760 (2019).
23. Unkovski-Korica, V. *Mining Companies and the EU Want Serbia's Lithium*. Jacobin [Internet]. 2022. Available from: https://jacobin.com/2022/01/serbian-lithium-rio-tinto-environmental-protest-movement-eu (2022).

24. The Guardian. *Rio Tinto Lithium Mine: Thousands of Protesters Block Roads Across Serbia*. The Guardian [Internet]. 2021. Available from: https://www.theguardian.com/world/2021/dec/05/rio-tinto-lithium-mine-thousands-of-protesters-block-roads-across-serbia (2021).
25. Agusdinata, D. B., Liu, W., Eakin, H. & Romero, H. Socio-environmental impacts of lithium mineral extraction: Towards a research agenda. *Environ. Res. Lett.* **13**(12), 123001 (2018).
26. Wanger, T. C. The lithium future—Resources, recycling, and the environment. *Conserv. Lett.* **4**(3), 202–206 (2011).
27. Reuter, B. Assessment of sustainability issues for the selection of materials and technologies during product design: A case study of lithium-ion batteries for electric vehicles. *Int. J. Interact. Des. Manuf.* **10**(3), 217–227 (2016).
28. Prior, T., Wäger, P. A., Stamp, A., Widmer, R. & Giurco, D. Sustainable governance of scarce metals: The case of lithium. *Sci. Total Environ.* **461**, 785–791 (2013).
29. Wang, Q. *et al.* Environmental impact analysis and process optimization of batteries based on life cycle assessment. *J. Clean. Prod.* **174**, 1262–1273 (2018).
30. Official Gazette of the Republic of Serbia. *Spatial Plan of the Area of Special Purpose for the Realization of the Project of Exploitation and Processing of Jadarite Minerals "Jadar"* No. 26 (2020).
31. Knežević, D., Nešić, A. & Cvijetić, A. Treatment and disposal of mine waste and extraction process and closure of landfill after completion of "Jadar" project. In *The Jadar Project—What is Known? Serbian Academy of Sciences and Arts, Scientific Conferences*, Vol. CCII. ISBN: 978-86-7025-924-9 87–106 (2021).
32. Official Gazette of the Republic of Serbia. *Water Management Strategy in the Territory of the Republic of Serbia Until 2034*, No. 3/2017 (2017).
33. Krizmanić, I. Živić, I., Niketić, M., Vukov, T., Ćirović, D., Kuzmanović, N., Vesović, N., Anđelković, M., Cvijanović, G., Nikolić, D., Penezić, A., Maričić, M., Bogdanović, N., Popović, M. & Lakušić, D. The Jadar project: Biodiversity and biological impacts. In *The Jadar Project—What is Known? Serbian Academy of Sciences and Arts, Scientific Conferences*, Vol. CCII. ISBN: 978-86-7025-924-9 157–176 (2021).
34. Toochi, E. C. Carbon sequestration: How much can forestry sequester CO_2. *For. Res. Eng. Int. J.* **2**(3), 148–150 (2018).
35. Mota, C. *Absorption of CO_2 by the Most Representative in the Region of Murcia Crops*. Report SCIC (2010).
36. Ontl, T. A. & Schulte, L. A. Soil carbon storage. *Nat. Educ. Know.* **3**(10), 35 (2012).
37. Björheden, R. *Climate Impact of Swedish Forestry*. Skogforsk reports, ISBN 978-91-88277-09-1 https://www.skogforsk.se/cd_20191216101138/contentassets/01f064719a434ecda8fcf0a0956755dc/climate-impact-of-swedish-forestry.pdf (2019).
38. Stendahl, J., Johansson, M. B., Eriksson, E., Nilsson, Å. & Langvall, O. Soil organic carbon in Swedish spruce and pine forests–differences in stock levels and regional patterns. *Silva Fenn.* **44**(1), 5–21 (2010).
39. Arafat, A. A. *Back Analysis of Mount Polley Tailing Dam Failure*. Master thesis, York University, Toronto, Canada (2017).
40. https://thenarwhal.ca/topics/mount-polley-mine-disaster/.
41. https://civil.ubc.ca/mount-polley-mine-tailings-present-in-quesnel-lake-water-eight-years-after-big-spill/.
42. https://www.savebristolbay.org/mt-polley-disaster.
43. Soldan, P., Pavonič, M., Bouček, J. & Kokeš, J. Baia Mare accident: Brief ecotoxicological report of Czech experts. *Ecotoxicol. Environ. Saf.* **49**, 255–261. https://doi.org/10.1006/eesa.2001.2070 (2001).
44. https://reliefweb.int/report/hungary/baia-mare-gold-mine-cyanide-spill-causes-impacts-and-liability.
45. https://media.greenpeace.org/archive/Cyanide-Spill-at-Aurul-Goldmine-in-Romania-27MZIFPWPWP.html.
46. https://www.telegraf.rs/english/2921659-the-name-of-the-serbian-river-is-chilling-one-of-the-most-polluted-rivers-in-the-world-and-there-are-no-life-forms-in-it-anymore-video.
47. Feasibility study of the underground exploitation of the lithium and boron deposit, Jadar, University of Belgrade—Faculty of Mining and Geology, Belgrade (2020).
48. Low regulation on permitted quantities of dangerous and harmful substances in land and water for irrigation and methods of their testing. Official Gazette of the Republic of Serbia. No 23 (1994).
49. Low regulation Rulebook on the hygienic correctness of drinking water (Official Gazette of the Republic of Serbia No 42/98 and 44/99 and No. 28/2019) (2019).
50. Low regulation Rulebook on the hygienic correctness of drinking water. Official gazette of the Republic of Serbia No. 28/2019 (2019).
51. Low regulation on limit values of polluting, harmful and dangerous substances in soil. Official gazette of the Republic of Serbia No 30/2018 (2018).
52. Low regulation on limit values of polluting, harmful and dangerous substances in soil. Official Gazette of the Republic of Serbia No 64/2019 (2019).
53. Ure, A., Quevauviller, P., Muntau, H. & Griepink, B. EUR Report. CEC Brussels, 14763, 85 (1992).
54. Bolan, S. *et al.* Boron contamination and its risk management in terrestrial and aquatic environmental settings. *Review. Sci. Total Environ.* **894**, 164744 (2023).
55. Soil, Ground Water and Sediment Standards for Use Under Part XV.1 of the Environmental Protection Act, Ministry of environment, Canada. https://dr6j45jk9xcmk.cloudfront.net/documents/998/3-6-3-sediment-standards-en.pdf (2011).
56. https://www.talisonlithium.com/greenbushes-project.
57. https://www.abc.net.au/news/2024-01-18/albermarle-kemerton-lithium-project-expansion-scaled-back-/103364330.
58. Graham, J. D., Rupp, J. A. & Brungard, E. Lithium in the green energy transition: The quest for both sustainability and security. *Sustainability* **13**(20), 11274 (2021).
59. Report and recommendations of the Environmental Protection Authority, Earl Grey Lithium Project, Covalent Lithium Pty Ltd, November 2019.
60. Earl Grey Lithium Project, Revised Proposal, Environmental Review Document prepared for Covalent Lithium Pty Ltd, April 2022, JBS&G Australia Pty Ltd.
61. Udruženje pčelara Loznica (Apiary Association of Loznica), member interview.
62. https://balkangreenenergynews.com/thousands-demand-revoking-serbias-commitments-to-rio-tinto/.

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